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Compression–bending behavior of a scaled immersion joint

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ABSTRACT

The mechanical behavior of an element joint of an immersed tunnel subjected to quasi-static axial compression and horizontal bending is investigated in this research. To explore the performance of the immersion joint compression–bending loads are applied on a scaled specimen in specific patterns, which are designed based on a practical project. It is found that the extension and closure of the immersion joint vary non-linearly with applied axial forces. Fitting equations for axial stiffness are correspondingly given with regard to loading and unloading states of the joint. Under bending action the element edges which constitute the immersion joint still remain plane. Observed rotations of the joint are non-linearly increasing with bending moment, whether it is pushed forward or bend inversely. Hysteresis behavior obviously exists and the hysteretic loop tends to contract with the increase of the axial force. The stiffness ratio of the joint with respect to that of the tunnel element in service states ranges from 1/360 to 1/120 for the axial stiffness, and from 1/29 to 1/212 for the flexural stiffness.

1. Introduction

An immersed tunnel consists of precast tunnel elements. The tunnel elements are being floated to the construction site and then are immersed in a trench excavated in the bottom of a water way. The immersion joints, which are connecting adjacent elements, are the weakest units in the whole tunnel (Ingerslev, 2010; ITA Working Group 11, 2011). According to the stiffness ratio of the joint to the element, immersion joints can be divided into three categories: rigid joints, flexible joints and partial-rigid (or partial-flexible) joints. Akimoto et al. (2002) summarized the types of immersion joint developed in Japan.

Whatever the type of immersion joint is, the design of it has to consider various actions during its service life, water pressure, earthquake, settlement of foundation, shock from shipwrecks, and other actions. Meanwhile, an immersion joint should include the water-proof part as an indispensable system. Therefore, knowledge of the deformation of a joint under loading is important for a safe, reliable, and water-proof design. Further, due to the water pressure in the construction phase, the immersion joint is submitted to an initial compression. It is vital to know the behavior of the immersion joint after immersion. Therefore, the axial stiffness for this situation is required for calculation and design.

Theoretically, the mechanical behavior of an immersion joint was considered under imposed deformation (Liu, 2009) or under seismic action (Anastasopoulos et al., 2007). Yu et al. (2014) deduced a bi-linear formula to account for the stiffness of a flexible joint, which was also verified through numerical modeling.

It should be noted that there are not much experimental works reported on immersion joints even though they came to practical applications for more than 100 years. Kiyomiya et al. (1992) performed a quasi-static test for the mechanical properties of a flexible joint with 1/4 geometric scale. In this test the flexural and compression behaviors of a joint were obtained. The results showed that the immersion joint behaved non-linearly in quasi-static and quasi-dynamic cases. Kiyomiya et al. (2004) also carried out both a 3-dimensional experiment and a finite element analysis for a new type of flexible joint referred to as the Crown Seal. Results of both tests indicated that this new type of joint can be applied in practice because of the effective reduction of deformation with this particular design. Hamazaki et al. (1999) applied a new type of steel device to the immersion joint. In these experiments, the axial and transversal mechanical properties of the joint were studied under static, cyclic and eccentric loading. The results showed that this device can play a role in energy dissipation. It can be seen that the behavior of immersion joints was often simplified

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as a bi-linear curve or the stiffness was regarded as a constant, which cannot reflect the real behavior of an immersion joint. However, former researchers mostly dealt with the response of a complete tunnel. Results in the tests done by Kiyomiya et al. (1992) also proved this. Moreover, only a few experiments were found about the flexural mechanical behavior of large-scale immersion joints as well as its flexural stiffness.

It should be noted that extension of the immersion joint may be caused from compression and tension due to different types of actions in tunnel elements. The differential extension of the immersion joint may be introduced as "snake" movement of an immersed tunnel along its longitudinal profile, whether from settlement of foundation or from stratum movement during earthquake (Owen and Scholl, 1981).

This paper presents a compression–bending static test of a half-flexible immersion joint with a 1:10 geometric scale. Modeling techniques for the scaled immersion joint were applied. For the experiment on the mechanical behavior of the immersion joint, considering the system model, measurement system and loading patterns, were defined. The compression on the scaled model is applied axially to simulate the water pressure on the immersion joint at typical buried depths. Bending moments are applied cyclically at equal amplitude in the horizontal plane, by varying the load in the axial hydraulic jacks on each sidewall of the element. Through observed load–deformation curves, both the axial stiffness and the flexural stiffness of the joint will be derived for use in practice.

2. Background

2.1. Immersion joints

As mentioned above, the immersion joints differ in stiffness and in this paper, the half-flexible one is presented. This choice is based on the real project of the Hong Kong–Zhuhai–Macao link which is under construction. The immersed tunnel in this project is approximately 5664 m in length. It consists of 33 elements and is finally connected to two artificial islands, as can be seen in Fig. 1.

The length of a typical element is 180 m and is assembled through 8 segments with 22.5 m in length between which are segmental joints. The cross-sectional dimension of the immersion joint is about 37.95 m $\times$ 11.40 m (Fig. 2(a)).

The partial-flexible immersion joint generally includes a GINA seal, an Omega water proof, shear keys and steel shell shown in Fig. 2.

When the immersed tunnel is installed, the GINA seal between elements will be pressed tightly with a minimum compression, resulting in a waterproof sealing due to initial water pressure. The initial water pressure varies from the depth of the immersion joint, resulting in different initial axial force in the joints. Therefore, the purpose of the GINA seal is to seal the immersion joints between two adjacent tunnel elements, ensuring the water tightness of the structure. If the GINA seal fails, the Omega water proof, as the second water tightness defense, will start to work to avoid severe leakage.

As a result of earthquake loading and differential settlement, ground motion will cause movement of the immersed tunnel. This movement will result in an extra axial force and a transversal force on the immersion joints (Van Oorsouw, 2010). The force in axial direction works on the cross section of the joint as well as the moment and they will be transferred from one element to another through the GINA seal. Moreover, shear keys are used to transfer transversal forces.

Hence, to study the flexural mechanical behavior of the immersion joint, only the GINA seal component is considered in this paper.

2.2. Deformation of immersion joint

From the researches by Owen and Scholl (1981), the deformation mode of underground structures subjected to earthquake loading can be divided into three categories: compression/extension, bending and racking. Regarding immersed tunnels, the first two modes dominate the deformation of immersion joint during earthquake.

In this study, the effect of longitudinal bending is mainly considered to express flexural mechanical behavior of immersion joints. As can be seen in Fig. 3, when the joint is subjected to axial force, the axial compression δ occurs in the joint. If the axial force and bending moment are applied together, the joint is compressed and rotates which means that both compression δ and rotation θ

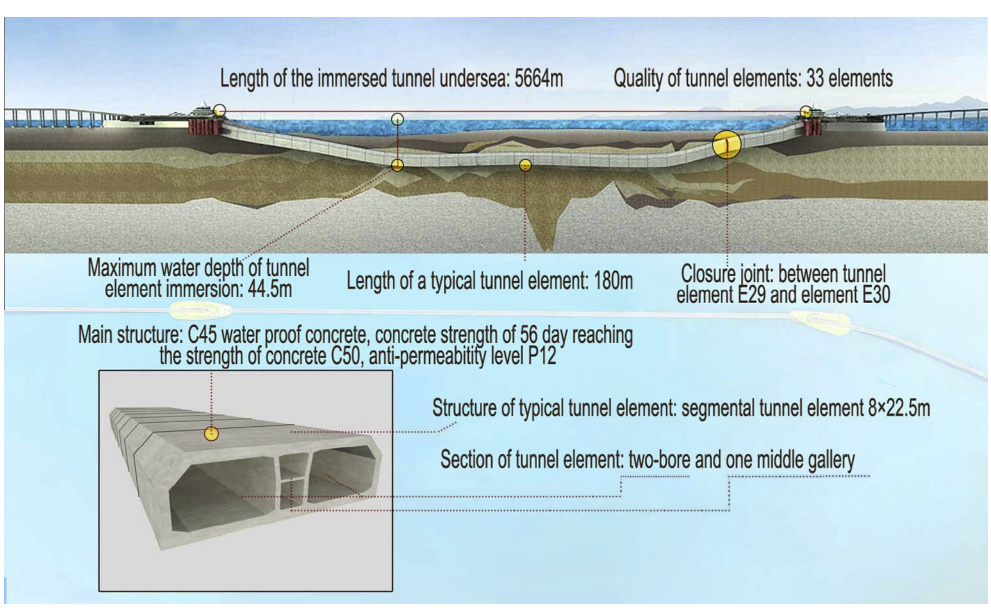

Fig. 1. Sketch of immersed tunnel in HZMB (CCCCHZMB, 2011).